Kicker and Septum Issues

Tom Mattison
University of British Columbia

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Introduction

The purpose of a kicker-septum system is to change the beam path
- Damping ring injection and extraction
- Fast beam abort for machine protection

A kicker is a fast pulsed magnet and associated power supply
- Energy stored in fields, risetime, falltime --> high power, high voltage
- Pulse amplitude stability, flatness

A septum is a magnet with two beam paths in different fields, usually "high" and "zero"
- High current density conductor, or thin iron web (Lambertson)
- Quality of field, on both beam paths
- Vulnerability to damage from the beam

The "obstacle" is the object that defines the separation between the beam paths.
- Usually the <u>outside</u> of a quadrupole or cryostat
- Usually both beam paths have "obstacles."

Usually it's impractical to do the entire path change with a kicker alone (voltage, power)
So the kicker moves the beam from one side of the septum to the other side.
The septum bends the kicked beam around the "obstacle"

Kickers and septa usually push parameters far outside the normal range
and are single-point-failure issues.

They need lots of dedicated, specialized engineering.

Cross-Cultural Issues

The optics of the two beam paths (drift distances, beta functions, apertures),
the absolute mechanical envelopes of the “obstacles,” the details of the septum design,
the details of the kicker magnet design, and the details of the kicker pulser design,
all interact very strongly.

It’s very easy for a beam optics designer or magnet/cryostat mechanical designer
to make a decision that makes the septum and/or kicker much more demanding.

The septum designer can make the kicker designer’s life much harder.

And the kicker magnet designer can make the pulser designer’s life harder.

The earlier in the design process that all these heads get together, the better.

Kicker Power

There is energy stored in the magnetic field of a kicker, proportional to the square of the field, the height, and the width. The pulser has to supply the energy in some length of time. The field strength integrated over the kicker length and the beam energy gives a deflection angle, and the drift length between the magnetic center of the kicker and the septum gives a deflection.

The power required in Watts is

$$P = u\frac{E^2\Delta^2 wh}{\eta\ell^3 t}$$

where $\boldsymbol{E}$ is beam energy in GeV, $\boldsymbol{\Delta}$ is beam displacement at the septum in meters, $\boldsymbol{w}$ and $\boldsymbol{h}$ are the kicker aperture width and height in meters, ℓ is the total length of the kicker plus drift region in meters, and $\boldsymbol{t}$ is the magnetic filling time (field risetime minus pulser risetim

η is the magnetic efficiency of the kicker, between 0 and 1, usually about 0.25.

In these units, the constant $u = 9.95\times10^6$

Built into this formula is the fact that the kicker itself should fill 2/3 of the total drift length

Cutting the total length in half requires a factor of 8 more power.

Doubling the apertures and deflection distance requires a factor of 16 more power.

Abort Kicker Power Example

If the beam energy is 500 GeV, the kicker apertures and the deflection at the septum are the full linac aperture (70 mm), the efficiency is 25%, and the length allocated is 100 meters, the power required to fill the kicker in 100 nsec is 2.4 GigaWatts!

A 50 Ohm coax cable run at 25 kV carries 12.5 MW of power. So this is 192 cables worth of power. A single thyratron tube can drive 2 to 4 cables, so it's 50-100 thyratrons.

We win rapidly if we can reduce the kicker apertures, and the ILC beam delivery system abort kicker design has a much smaller aperture, so the total power is only 225 MW.

Abort Kicker Pulse Length and Rate Issues

Kickers nearly always have a resistive load someplace (the power is NOT dissipated in the magnet itself!)

The abort pulse length spec is not yet well defined. It needs to be as long as the bunch train, but there may be ways to abort much of the beam upstream, so the pulse length might need to be only several microseconds rather than a millisecond.

For long pulses, the stored energy in the source, and the dissipation in the load, get unreasonable. So one starts to consider schemes with high peak power for filling, and low sustaining power to maintain the field against resistance in cables and the magnet, but not the resistance of the load. This clearly complicates the engineering of the pulser and load, but perhaps less so than dealing with the high stored energy and dissipation.

The beam delivery abort dump will also be used as a tune-up dump. If the kicker is implemented as striplines, it is fairly easy to wrap a DC magnet around the whole thing for this purpuse.

It's not clear whether the tune-up dump will be designed for the full beam power, or only a low total power, implying a low pulse rate and/or short bunch train. There may be some cost savings in the kicker if it does not need to run at full 5 Hz rate

Other Kickers in ILC

There are probably several other beam-abort kickers upstream, in the RTML and before the positron undulator. Others might get invented along the linac. These will have specs similar to the beam delivery abort kicker, except lower beam energy. Their dumps will also be used as tune-up dumps.

Damping rings obviously need kickers. The risetime needs to be much faster, and there is also a tight reproducibility spec, a high burst-rate spec (3 MHz), and a falltime spec.

There are many, many hands stirring this pot (I'm not included at this point). We'll just have to ask for guidance from the Damping Ring folks about which version to cost for.

The ring extraction kicker may also be the "beam abort" kicker for the ring. If so, the pulser would have to work in long-pulse mode, which may or may not be compatible with peoples' thoughts about how to do the pulser.

Kicker Cost Optimization

There is a tradeoff between length and pulser power, both of which will be significant cost drivers. The total cost can be written $C = C_L \ell + C_P P$ where C_L is the cost per meter of tunnel (including the kicker and vacuum system), and C_P is the cost per Watt of peak power.

We can then write

$$C = C_L \ell + C_P u \frac{E^2 \Delta^2 wh}{\eta \ell^3 t}.$$

The length that minimizes the cost is the solution of

$$C_L - 3C_P u \frac{E^2 \Delta^2 wh}{\eta t} \ell^{-4} = 0$$

which is

$$\ell = \sqrt[4]{\frac{3C_P u E^2 \Delta^2 wh}{C_L \eta t}}.$$

We can also write this as

$$\ell = \sqrt[4]{\Delta^2 wh} \frac{\sqrt{E}}{\sqrt[4]{t}} \sqrt[4]{\frac{C_P}{C_L}} \sqrt[4]{3u}.$$

Kicker Cost Optimization

The factor $\Delta^2 wh$ scales roughly as the fourth power of the aperture a, so we can write

$$\ell = a \frac{\sqrt{E}}{\sqrt[4]{\eta t}} \sqrt[4]{\frac{C_P}{C_L}} \sqrt[4]{3u} \,.$$

The cost-optimum length is proportional the square-root of beam energy, roughly proportional to the aperture, inversely with the fourth root of the product of the required risetime and the kicker structure efficiency, times the fourth root of the ratio of the cost per Watt and the cost per meter.

It would take a factor of 16 change in the cost ratio, the required risetime, or the kicker structure efficiency to change the optimum length by a factor of 2.

But changes in aperture show up directly in length (and cost).

Kicker Cost Optimization

At the minimum, the total cost over total length is

$$C_L + C_P u \frac{E^2 \Delta^2 wh}{\eta t} \left(\sqrt[4]{\frac{3 C_P u E^2 \Delta^2 wh}{C_L \eta t}} \right)^{-4} = C_L + \frac{C_L}{3}.$$

So <u>the cost-optimum is to spend three times as much money on length as on power</u>.

Also, <u>the total cost at the optimum will simply be proportional to the length</u>.

If the length is set arbitrarily rather than by optimization, the system cost will be larger.

If the length is twice the optimum, the length-dependent cost is doubled, from 3/4 to 6/4, and the power-dependent cost is reduced from 1/4 to 1/32, so the total cost is 53% higher than optimal.

But if the length is half the optimum, while the length cost goes from 3/4 to 3/8, the power cost goes up a factor of 8, from 1/4 to 2, <u>more than doubling the total cost</u> compared to the optimum. This may be an underestimate, because the cost per length of the kicker structure may no longer be small compared to the cost per length of tunnel, since we are putting 8 times the power into 1/2 the length compared to the cost-optimal solution.

So the cost risk of allocating too little space for a kicker is higher than the cost risk of allocating too much.

EDIA Issues

Kickers need lots of engineering, by pulsed power engineers, and their technicians. Figure on building prototype pulsers and magnets of each type, measuring them, blowing up a few, revising the designs, building more prototypes. There will need to be quite a bit of measurement equipment, since the beam will not be available as a diagnostic.

This keeps the engineers and technicians busy for up to quite a few man-years, depending on how far the parameters have been pushed.

Then figure on having duplicate pulsers and magnets outside the machine that will be busy during machine commissioning, when people are trying to figure out how to make them perform up to spec, or why they are failing and what to do about it.

Hopefully the various abort kickers can be made similar enough to partially amortize this.

The damping ring kickers will need separate facilities like this.

Septum Issues

The total deflection required is determined by the apertures of the two beam paths, including any beam pipes if the septum itself is not in vacuum, and the septum thickness.

We want the total deflection to be as small as possible, to make the kicker easier, so we want the septum thickness as small as possible.

For a current-sheet septum, the current required is proportional to the field strength difference between the two sides. If the septum is thinner, the current density goes up.

Septum magnets push the current density to absurd values. Up to 80 amps per square millimeter has been done, but only by having parallel water flow through each conductor, and conductor lengths of only a meter. At 80 amps/mm^2, we get 1 kG of field per millimeter of septum thickness (independent of aperture).

Magnets of several meters length would have to work at lower current density (say 40 amps/mm^2 at 3-4 meter length). There would still be a rats-nest of water connections at each magnet end, and the magnets could not be packed very close together.

Septum magnets at these current densities will self-destruct in a few seconds if there is a glitch in any of the cooling passages. They need lots of separate thermal interlocks.

Damping ring septa have tight requirements on the leakage into the stored beam path. Usually there is an extra small power supply for “backleg windings.”